

Draft Executive Summary:

Evaluation of Conversion Technology Processes and Products

September 2004

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Executive Summary

The diversion of materials from landfill is one of the central goals of the California Integrated Waste Management Board (CIWMB) as well as an important societal issue. Diversion efforts have increased substantially in California since the passage of the Integrated Waste Management Act in 1989, which established a target of 50 percent diversion from landfills by 2000. Although the diversion rate in California is estimated to be approximately 47 percent, more than 39 million tons of material is still disposed of in landfills.

Of the materials landfilled, 79 percent is organic (biomass and plastic carbonaceous material) and could potentially be processed to provide chemical energy or be converted into other useful products. For example, the 31 million tons of organic waste currently landfilled annually contains the equivalent energy of more than 60 million barrels of crude oil, or could support 2500 MW of electrical power or 22.1 TWh^{*} of electric energy (if all energetic components were to be converted to electricity by conventional means), representing about 10 percent of the in-state electrical generation and about 8 percent of the State's electric energy consumption (276.6 TWh/year).

Potential options for reducing the current amount of waste disposed in landfills include reducing the generation of waste, increasing the amount recycled, and/or diverting a portion of the stream through other conversion processes. The recycling market plays an important role in the waste infrastructure. Much of the readily recyclable material is already pulled from the waste stream due to market and local jurisdiction efforts to satisfy diversion required by the Integrated Waste Management Act. Programs to reduce waste at the source (i.e., producer responsibility laws) are also used elsewhere, such as Europe.

Although these programs have had some success, it is unlikely that these source reduction programs will be widely adopted in the United States without greater public and political support. The combustion or incineration of waste is another option that has increasingly been used in Europe and Japan where strict environmental regulations are in force. Incineration remains controversial, however, due to public perceptions of environmental impacts and other issues even though combustion systems have been significantly improved in recent years. Barriers to waste incineration will probably not be overcome in California in the foreseeable future.

To further explore options for reducing the landfill disposal of organics, legislators and the CIWMB have put in place several new programs. Assembly Bill 2770 (Matthews, Chapter 740, Statutes of 2002) initiates information-gathering activities, including this report, which evaluates technology options, life-cycle analyses, and market assessments.[†]

A main focus of these programs includes the evaluation of conversion technologies, or methods that do not employ full oxidative combustion (commonly called incineration). These include thermochemical processes such as pyrolysis and gasification and biochemical processes such as aerobic and anaerobic digestion and fermentation. Questions pertaining to these technologies include the types of feedstocks that can potentially be utilized, the technical viability of the processes, the products from the processes, their environmental impacts, and financial, economic, social, and political feasibility.

This report provides a technical evaluation of alternative conversion technologies, addressing issues related to technical viability and environmental impacts. As part of this evaluation, a survey of

^{*} A terawatt hour (TWh) is the equivalent of 1 million megawatt hours (MWh)

[†] AB 2770 also includes a definition for gasification that is technically inaccurate.

companies, institutions, and technology developers was conducted in combination with an evaluation of information available in the open literature. An extensive database of companies, institutions, and technology developers were surveyed by questionnaire. This database was developed through separate work funded by CIWMB (available at <http://cbe1.engr.ucdavis.edu/conv/home.htm>).

The survey questions addressed issues such as commercial status, typical feedstocks, applicability to municipal solid waste (MSW), and information about the performance of the technology such as energy conversion efficiency and mass reduction efficiency. Of the nearly 400 companies, institutions, and technology developers that we initially contacted or attempted to contact, a total of 69 responded. This included information on 18 pyrolysis technologies, 22 gasification technologies, 11 biochemical processes, 10 plasma arc technologies, and 9 technologies related to catalytic cracking, feedstock preparation, or other issues.

Of these responses, approximately 70 percent provided answers to the survey questions in varying level of detail, with remaining responders providing supplementary materials. The focus of this report is an overall technical evaluation, but certain social, economic, and regulatory issues are addressed as appropriate. Although information was obtained from organizations with a commercial interest in alternative conversion technologies, a formal vendor evaluation was not conducted.

Based on the information gathered, the relative merits of the various conversion technologies were evaluated with emphasis on the following criteria: (a) reduction in total MSW mass flow to landfills, (b) environmental impact and (c) creation of revenue from the marketing of useful energy products. This program is part of the larger effort that includes a life cycle analysis (LCA) by RTI International and a market analysis by Hilton Farnkopf & Hobson, LLC.

Conversion Pathway Definitions

An important aspect of this report is to provide consistent and accurate conversion process definitions that can be utilized in legislative or other areas. Although AB 2770 includes a definition for gasification, from a scientific standpoint this definition is overly restrictive and does not encompass the full range of technologies available. Under this definition, processes that gasify waste to produce clean burning fuels for uses other than electricity generation would not be considered gasification. Consequently, these processes would be ineligible for exclusion from the definition of transformation. Gasification processes that use small amounts of oxygen or air internally as a reactant to generate the heat necessary for gasification would also be excluded. Confusion also exists in literature regarding the definitions of “incineration” and “combustion.” For these reasons, separate definitions were developed and clearly described for the processes covered under this report.

Conversion of organic material can proceed along three main pathways:

- Thermochemical
- Biochemical
- Physicochemical

Thermochemical Conversion Pathways

Thermochemical conversion is characterized by higher temperatures and conversion rates than most other processes. Thermochemical conversion includes a continuum of processes ranging from thermal decomposition in a primarily non-reactive environment (commonly called pyrolysis) to decomposition in a chemically reactive environment (usually called gasification if the products are primarily fuel gases or

complete combustion if the products are fully oxidized). Pyrolysis can be considered an incomplete gasification process, in which a mixture of gaseous, liquid and solid products is produced, each of which may have some immediate use to sustain the process. The characteristics of each of these processes can also vary depending on the oxidizing or reducing media, process temperature and process pressure.

Combustion Definition

Combustion is the oxidation of the fuel for the production of heat at elevated temperatures without generating commercially useful intermediate fuel gases, liquids, or solids. Combustion of MSW or other secondary materials is generally referred to as incineration. Flame temperatures range typically between 1500 and 3000°F depending on fuel, oxidant, stoichiometry, furnace design, and system heat loss. Particle temperatures in heterogeneous (e.g. unsteady reactions between solid and gas phases) combustion can differ from the surrounding gas temperatures, depending on radiation heat transfer conditions.

Combustion of solids involves the simultaneous processes of heat and mass transport, progressive pyrolysis, gasification, ignition, and burning, with no intermediate steps and with an unsteady, sometimes turbulent, fluid flow. Normally, combustion employs an excess of oxidizer to ensure maximum fuel conversion, but it can also occur under fuel-rich conditions. Products of combustion processes include heat, oxidized species (e.g. carbon dioxide [CO₂], water [H₂O]), products of incomplete combustion and other reaction products (mostly as pollutants), and ash. Other processes, such as supercritical water oxidation and electrochemical oxidation can produce similar end products at lower temperatures but higher pressures.

Gasification Definition

Gasification typically refers to conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation using substoichiometric air or oxygen to produce fuel gases (synthesis gas, producer gas), principally CO, H₂, methane, and lighter hydrocarbons in association with CO₂ and N₂ depending on the process used. Alternative configurations using either indirect heating methods such as externally fired burners or autothermal methods using exothermic reducing reactions have been demonstrated.

While gasification processes vary considerably, typically gasifiers operate from 1300° F and higher and from atmospheric pressure to five atmospheres or higher. The process is generally optimized to produce fuel or feedstock gases. Gasification processes also produce a solid residue as a char, ash, or slag. The product fuel gases, including hydrogen, can be used in internal and external combustion engines, fuel cells, and other prime movers for heat and mechanical or electrical power. Gasification products can be used to produce methanol, Fischer-Tropsch (FT) liquids, and other fuel liquids and chemicals (see Chapter 4).

Gasification of solids with subsequent combustion of the gasification-derived fuel gases generates the same categories of products as direct combustion of solids, but pollution control and conversion efficiencies may be improved. Alternatively, the produced synthesis gases can be used directly for liquid fuel or chemical synthesis, eliminating or delaying the combustion process and the emission of resulting effluent.

Pyrolysis Definition

Pyrolysis is a process similar to gasification except generally optimized for the production of fuel liquids (pyrolysis oils) that can be used straight (e.g. as boiler fuel) or refined for higher quality uses such as

engine fuels, chemicals, adhesives, and other products. Pyrolysis also produces fuel gases, and the solid residue contains most of the inorganic portion of the feedstock as well as large amounts of solid carbon or char.

Usually, a process that thermochemically degrades material without the addition of any air or oxygen is considered pyrolysis. Pyrolysis typically occurs at temperatures in the range of 750-1500° F. Pyrolysis and combustion of pyrolysis-derived fuel liquids and gases also produce the same categories of end products as direct combustion of solids. Like gasification, their pollution control and conversion efficiencies may be improved. Where fuel liquids are produced, the eventual site of emission of combustion products may be considerably displaced from the source of fuel production (e.g., vehicle emissions).

Plasma arc and radio frequency (or microwave) heating refer to specific devices providing heat from electricity for gasification, pyrolysis, or combustion depending on the amount of reactive oxygen, hydrogen, steam, or other reactant fed to the reactor. Plasma arc processes use electricity passing through electrodes to produce a discharge converting the surrounding gas to an ionized gas or plasma. Gases heated in plasmas typically reach temperatures of 7000° F and higher.

Catalytic cracking is a thermochemical process that employs catalysts using hydrogen-driven reducing reactions to accelerate the breakdown of high molecular weight compounds (e.g. plastics) into smaller products for the purposes of improving selectivity and imparting certain desirable characteristics to the final product, such as volatility and flashpoint of liquid fuels. This cracking process is often employed in oil refinery operations to produce lower molecular weight hydrocarbon fuels from waste feedstocks. These include gasoline from heavier oils, distillation residuals, and waste plastic.

Biochemical Conversion Pathways

Biochemical conversion proceeds at lower temperatures and lower reaction rates and can offer high selectivity for products. Higher moisture feedstocks are generally good candidates for biochemical processes. Non-biodegradable organic feedstocks, such as most plastics, are not convertible by biochemical processes.

Anaerobic Digestion Definition

Anaerobic digestion is a bacterial fermentation process that is sometimes employed in wastewater treatment for sludge degradation and stabilization. This is also the principal process occurring in the decomposition of food wastes and other biomass in landfills. Anaerobic digestion operates without free oxygen and results in a fuel gas called biogas, containing mostly CH₄ and CO₂ but frequently carrying other substances such as moisture, hydrogen sulfide (H₂S), and particulate matter that are generally removed prior to use of the biogas.

Anaerobic digestion is known to occur over a wide temperature range from 50 to 160° F. Anaerobic digestion requires attention to the nutritional needs and the maintenance of reasonable temperatures for the facultative and methanogenic bacteria degrading the waste substrates. The carbon/nitrogen (C/N) ratio of the feedstock is especially important. Biogas can be used after appropriate gas cleanup as a fuel for engines, gas turbines, fuel cells, boilers, industrial heaters, other processes, and the manufacturing of chemicals. Anaerobic digestion is also being explored as a route for direct conversion to hydrogen.

Aerobic Processing Definition

Aerobic conversion includes most commercial composting and activated sludge wastewater treatment processes. Aerobic conversion uses air or oxygen to support the metabolism of the aerobic microorganisms degrading the substrate. Nutritional considerations are also important to the proper functioning of aerobic processes. Aerobic processes operate at much higher reaction rates than anaerobic processes and produce more cell mass, but generally do not produce useful fuel gases. Aerobic decomposition can occur from as low as near freezing to about 160° F.

Fermentation Definition

Fermentation is generally used industrially to convert substrates such as glucose to ethanol for use in beverage, fuel, and chemical applications and to other chemicals (e.g., lactic acid used in producing renewable plastics) and products (e.g., enzymes for detergents). Strictly speaking, fermentation is an enzymatically controlled anaerobic process although the term is sometimes more loosely applied to include aerobic processing as well.

Fermentation feedstocks require pretreatment by chemical, physical, or biological means to open up the structure of biomass and reduce the complex carbohydrates to simple sugars. This set of pretreatments is often referred to as hydrolysis. The resulting sugars can then be fermented by the yeast and bacteria employed in the process. Feedstocks high in starch and sugar are most easily hydrolyzed. Cellulosic feedstocks, including the major fraction of organics in MSW, are more difficult to hydrolyze, requiring more extensive pretreatment.

Ethanol and carbon dioxide are the primary products of glucose fermentation by yeast. Ethanol inhibits microbial growth and fermentation, often essentially halting the fermentation when the ethanol concentration reaches about 12 percent. Ethanol must be removed from the fermentation broth to be used as fuel.

Processes are also in development that would convert ethanol to hydrogen without distillation. Although ethanol fermentation and anaerobic digestion are commonly classified separately, both are fermentation. Lignin in biomass is resistant to fermentation. Process residuals are typically considered for compost, boiler fuel, animal feed, or as a feedstock for thermochemical conversion to other fuels and products.

A summary schematic of thermochemical and biochemical processing of MSW is presented in Figure ES-1.

Physicochemical Conversion Pathways

Physicochemical conversion involves the synthesis of products using physical and chemical processing at near-ambient temperatures and pressures. It is primarily associated with the transformation of fresh or used vegetable oils, animal fats, greases, tallow, and other suitable feedstocks into useful liquid fuels and chemicals such as biodiesel, frequently by transesterification, a reaction of an organic glyceride with alcohol in the presence of catalyst.

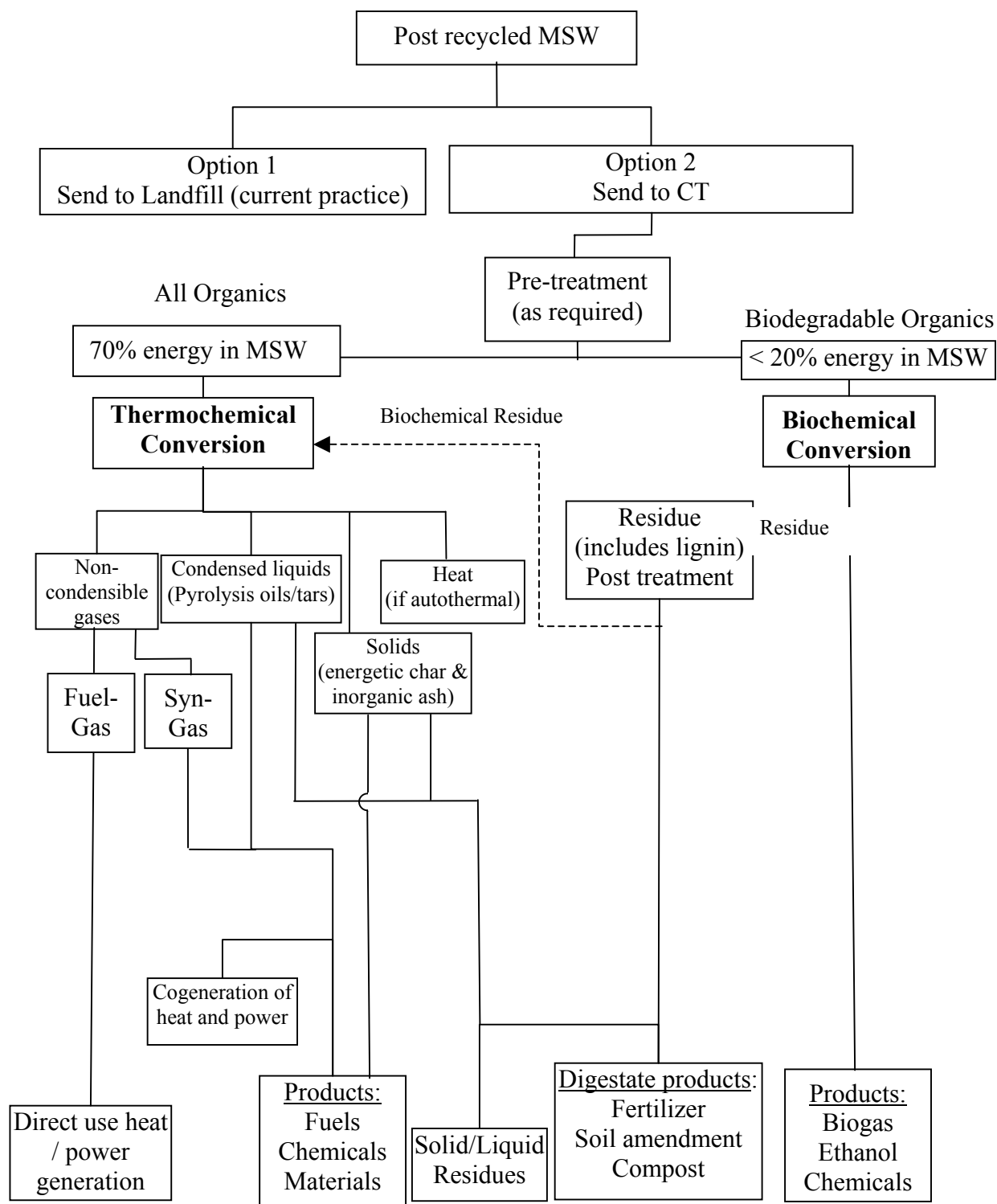


Figure ES - 1: A General Schematic of the Flows and Products from Processing Post-recycled MSW with Conversion Technologies.

Feedstocks

Feedstocks that can be utilized with alternative conversion processes are primarily the organic materials now being landfilled (organic means “containing carbon and hydrogen”). These include paper, cardboard, plastic, food waste, green waste, and other waste. A summary of the waste material currently being landfilled, including the potential chemical energy of each component, is provided in Table ES-1.[‡]

Thermochemical processes can potentially convert all the organic portion of the waste stream that is currently going to landfill into heat and other useful products. Because most thermochemical processes operate at elevated temperatures, the fate of trace inorganic elements, such as metals that may be present in MSW, needs to be considered in the process design. Some further sorting and/or processing of post-materials recovery facility (MRF) MSW would normally be conducted prior to thermal conversion to reduce particle sizes to those compatible with the process, and dry the material if needed.

Another element of the sorting process would be to remove, to the extent possible, materials such as PVC, batteries, or feedstocks with copper (Cu) that can contribute to the formation of toxic emissions. Metals, glass, and ash do not contribute substantially to energy value in thermochemical processing but may be substantially transformed due to the high temperatures involved. Plastics are also converted by thermochemical processing.

Biochemical processes can convert only the biodegradable fraction of feedstocks. Metals, glass, mineral matter, and most of the current waste plastic stream are inert to biodegradation. Some of the newer plastics include biodegradable fractions or are fully biodegradable. The fraction of these plastics in the waste stream is currently very small but may increase over time. Higher-moisture feedstocks tend to be good candidates for biochemical processes, partly because of the extra energy required for drying before use in most thermochemical processes.

Biochemical conversion technologies prefer source-separated green or food waste, or the biogenic fraction of mixed MSW after sorting. Some biochemical systems (so-called “high solids” reactors) can accept unsorted MSW (shredded or crushed to appropriate size) in the reactor, though this is suboptimal from the standpoint of material handling, reactor volume utilization, and disposal or use of residuals.

Paper and cardboard is the largest category of materials (on both a mass and energy basis) currently landfilled that could be processed by conversion technologies. Paper and cardboard material comprise 11 million tons or 30 percent of the materials currently landfilled. On an energy basis, paper and cardboard represents nearly half (44 percent) of the potential chemical energy in the waste stream. Although recycling of old corrugated containers (OCC) and old newspaper (ONP) materials is a well developed industry in California, the recycling rates for these components are still only 52 and 58 percent, respectively.

The collection of materials is a consideration with recycling of OCC and ONP, including the problem of capturing OCC from small businesses. Mixed paper is also recycled, though the value of mixed paper as a commodity has been historically relatively low. More recently, the export market, particularly to China, has resulted in significantly higher prices paid for mixed paper grades.

[‡] This summary of the landfilled waste stream in California uses 2003 disposal amounts and 1999 waste characterization data. The CIWMB is currently updating the statewide landfilled waste characterization.

Table ES-1. California Annual Landfilled Waste Stream Characterization with Estimated Chemical Energy Content by Component

	Landfilled ^{a,d} (million tons)	Fraction of Total ^d (% wt.)	Moisture ^b (%wb)	Landfilled (million tons, dry)	Ash / mineral matter (million tons)	HHV ^b (BTU/dry lb)	Potential Chemical Energy (PJ) ^c	Equivalent barrels of crude oil (millions)	Potential Chemical Energy	
									Fraction of total (%)	(rank)
Paper/Cardboard	11.3	30.3	10	10.2	0.60	7650	164	27	44.2	1
Food	5.9	15.7	70	1.8	0.29	6000	22	4	6.0	5
Leaves and Grass	3.0	7.9	60	1.2	0.12	6450	16	3	4.4	7
Other Organics	2.6	6.9	4	2.5	0.26	3800	20	3	5.4	6
C&D Lumber	1.8	4.9	12	1.6	0.09	8300	28	5	7.5	4
Prunings, trimmings, branches and stumps	0.9	2.3	40	0.5	0.03	8175	9	1	2.5	9
Biomass Components of MSW Total	25.5	68.0		17.8	1.4		261	42	70.0	
All non-Film Plastic	1.9	5.0	0.2	1.9	0.04	9475	38	6	10.2	3
Film Plastic	1.5	3.9	0.2	1.5	0.04	19400	59	10	16.5	2
Textiles	0.8	2.1	10	0.7	0.06	8325	13	2	3.4	8
Non-Biomass Organic Components of MSW Total	4.1	11.0		4.0	0.14		110	18	30.0	
Other C&D	2.5	6.7		2.5	2.5	-				
Metal	2.3	6.1		2.3	2.3	-				
Other Mixed and Mineralized	2.0	5.3		2.0	2.0	-				
Glass	1.1	2.9		1.1	1.1	-				
Inorganic Components of MSW Total	7.8	20.9		7.8	7.8	0	0	0	0	
Totals (1999)^d	37.4	100		29.7	9.4	(ave.)	370	60	100	
Estimate for 2003^d	39.8			31.6	10.0	5900	394	64		

a) California waste stream composite data (<http://www.ciwmb.ca.gov/WasteChar/Study1999/OverTabl.htm>), Accessed 3 May, 2004

& California Solid Waste Generation and Diversion (<http://www.ciwmb.ca.gov/lccentral/Rates/Diversion/RateTable.htm>) Accessed 3 May, 2004

b) Adapted from Tchobanoglous, G., Theisen, H. and Vigil, S.(1993),"Integrated Solid Waste Management", Chapter 4, McGraw-Hill, New York

& Themelis, N. J., Kim, Y. H., and Brady, M. H. (2002). "Energy recovery from New York City municipal solid wastes." Waste Management & Research, 20(3), 223-233

c) 100 PJ/yr is equivalent to 3.2 GW of chemical energy used continuously throughout the year

d) The latest Waste characterization data publicly available is from 1999. Potential Energy in 2003 disposal was estimated using the 1999 characterization. CIWMB is currently conducting a new characterization of the disposed waste stream and can be used in the 2003 energy estimate when available.

Overall, the paper and cardboard recycling rate in California is slightly higher than 30 percent, or 4.5 million tons of material. Increase in demand for paper for recycling will depend on new efforts by government and the private sector to utilize products made with a higher percentage of recycled-paper content.

From an energy standpoint, plastics and other organic components of fossil origin in MSW are the second-largest component of the waste stream, representing some 30 percent of the chemical energy. On a weight basis, plastics and textiles represent 11 percent or 4.2 million tons of material landfilled. On a volumetric basis, plastic materials occupy as much as 22 percent of the space in a landfill due to their comparatively lower density. Plastic materials present in the waste stream in the highest amounts include high-density polyethylene (HDPE), polyethylene terephthalate (PET), film plastics, and other durable plastics.

Although some plastic recycling markets are well developed, the overall recovery fraction of plastics is only about 5 percent. PET bottles have the highest recycling rate at approximately 35 percent. HDPE containers are the next-highest category of recycled plastics with a rate of 13 percent. The cost of collecting and processing waste plastics typically exceeds the value of the material. The number of new plastic containers has also increased in recent years, resulting in corresponding decreases in the overall recycling rate even though the total amount recycled has increased.

With a high percentage of the total available chemical energy in mixed MSW, non-recycled plastics could be attractive materials for alternative conversion processes. Thermochemical processes currently represent the only means for plastics conversion. With the appropriate thermochemical processes, gasoline, diesel, and other fuels could be produced as well as petroleum-like base products such as ethylene for new plastics production. These would displace fossil petroleum use.

Thermochemical techniques have previously been developed for plastics recycling. These conversion technologies could also be applied to the growing problem areas of electronic components, consumer appliances, and plastic packaging materials. Since chlorine is a precursor to dioxin formation, the chlorinated plastics components (PVC) would either have to be separated from the feed stream or include appropriate remediation technology in the process.

Primary feedstocks for biochemical processes would be green and food wastes, although other biomass could also be used. Lignin is largely undegraded in most fermentation systems, including anaerobic digestion and hence remains as a residue of the process. Lignin represents approximately 28 percent of typical softwood, up to 50 percent for nut shells, with lower percentages for grasses, straws, and other herbaceous materials. Paper is primarily cellulose but may be coated or otherwise treated and include other constituents such as clay and heavy metals from pigments. Sludge products may have value as fertilizer or soil additives if heavy metal concentrations can be kept sufficiently low. The lower temperatures of biochemical treatment have some advantages in terms of reducing the potential formation of pollutant and hazardous species compared with higher temperature thermal processes, but cannot process the full waste stream.

Thermochemical Process Descriptions and Current Status

Pyrolysis and gasification systems tend to employ several common steps, although system designs vary by manufacturer. These steps include feedstock preparation and introduction into the reactor, the reaction of the waste through application of heat or addition of other reactants such as air, oxygen, steam, hydrogen, post combustion or processing of the gases produced during the reaction step, and the management of the resulting liquids, char, and ash.

Schematic diagrams of pyrolysis and gasification processes are shown in Figures ES-2 and ES-3. Since a number of gasification systems incorporate pyrolysis units prior to the gasification unit, the general gasification schematic includes an upfront pyrolysis unit in addition to the main gasification reactor but this may not always be present.

The preparation and means of introducing the feedstock into the reactor depend on the specific nature of the waste being processed. Shredding or size reduction is often used to facilitate handling and help promote the reaction of the feedstock in the pyrolyzer or gasifier. Drying of the feedstock is also needed for some processes, although the degree of drying is process-dependent. Some processes are capable of handling moist/undried MSW or other waste while others require dry feedstock. Introduction of the feedstock in the form of an aqueous slurry is possible in some processes.

For MSW, an additional processing step is often used to recover inert and recyclable materials such as metal and glass that will not react in the gasification or pyrolysis processes. Upstream separation of certain plastics and paper would probably also be used to recover any potentially recyclable material before the reactor. Upstream sorting processes can also be used for the removal of green waste and other moist organics in order to provide a feedstock with lower moisture content. Sorted MSW can also be pelletized or otherwise densified into a refuse-derived fuel (RDF).

The reaction vessel itself is one of the most variable components of the system design. Reactors can typically be characterized as either vertical or horizontal. A rotary kiln is an example of a horizontal reactor. The three main types of vertical reactors are fixed bed, fluidized bed, and entrained bed. For the fixed bed systems, the feedstock is typically fed onto a grate with either up-, down-, or cross-draft flow of gases. In practice the bed is not usually actually fixed, but moves through the system either by active or passive (e.g. settling) processes.

In an updraft flow or countercurrent reactor, the air or oxygen supply is injected from the bottom, the feed from the top, and the product gases are extracted from the top of the reactor vessel while the solids move downward to be removed through the grate. In a downdraft, co-current flow reactor, the air generally enters near the top of the reactor along with the feed and products are extracted near the bottom of the reactor.

In a fluidized bed reactor, the reactor bed consists of inert particles (usually sand or alumina) sometimes containing a catalyst. Gas or air introduced below the bed causes the particles to become suspended, making the reactor contents behave like a liquid. Feedstock can be fed directly into the bed or introduced above the bed. The feedstock and bed particles undergo continuous agitation and mixing during the process to provide a more uniform temperature distribution and improved heat transfer. In a bubbling bed reactor, the oxygen, air, steam, or other carrier or reactant fluid used to fluidize the bed is injected at a velocity that is high enough to suspend the bulk of the solids on the gas until the feedstock particle size has become sufficiently small due to reaction. In a circulating fluidized bed, the gas velocity is increased so as to entrain a large fraction of the bed with subsequent active removal and recirculation of bed particles producing a more uniform distribution throughout the reactor. Other reactor designs include open hearth, tubular and cylindrical tank reactors.

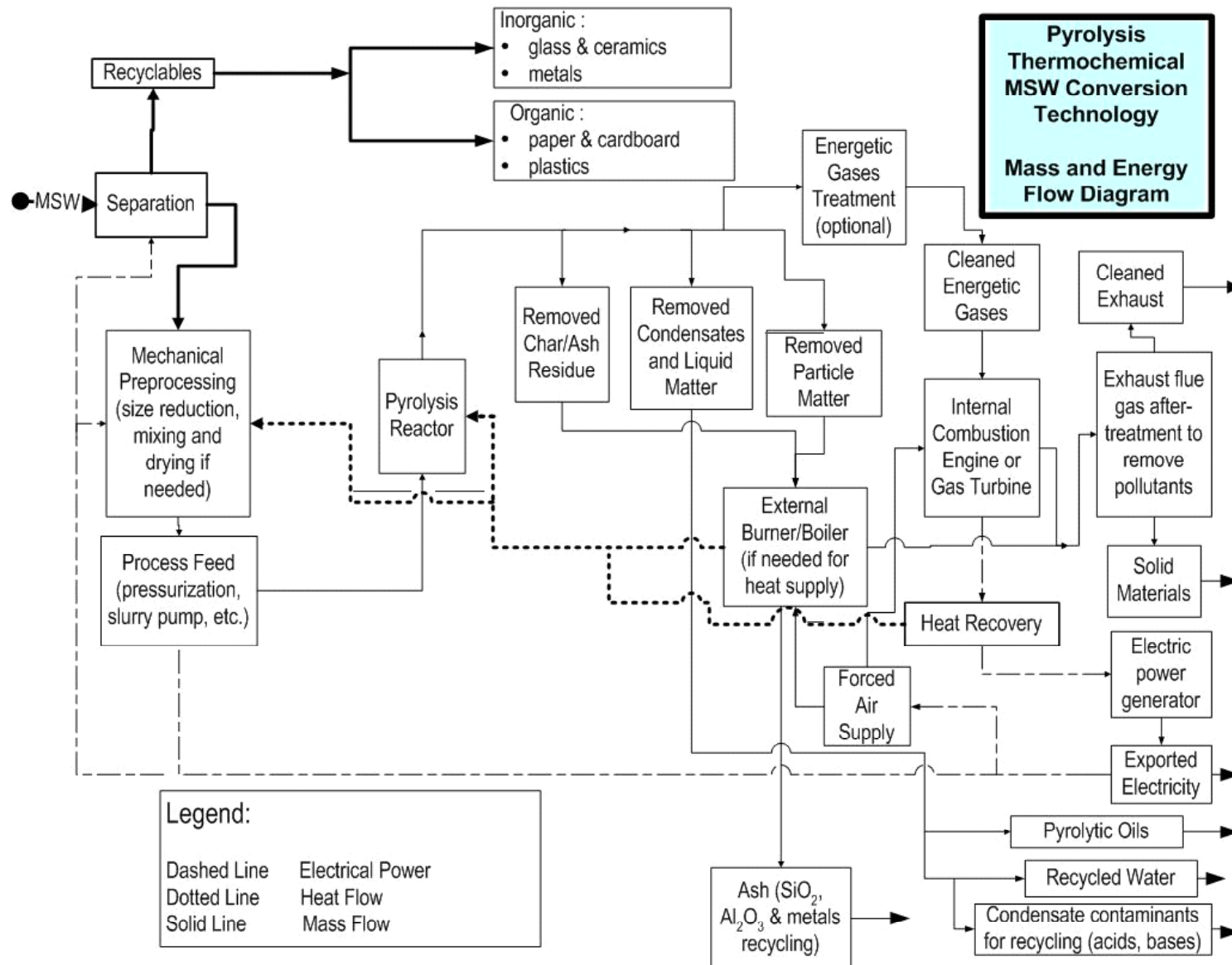


Fig. ES - 2: Schematic Diagram of a Pyrolysis Process.

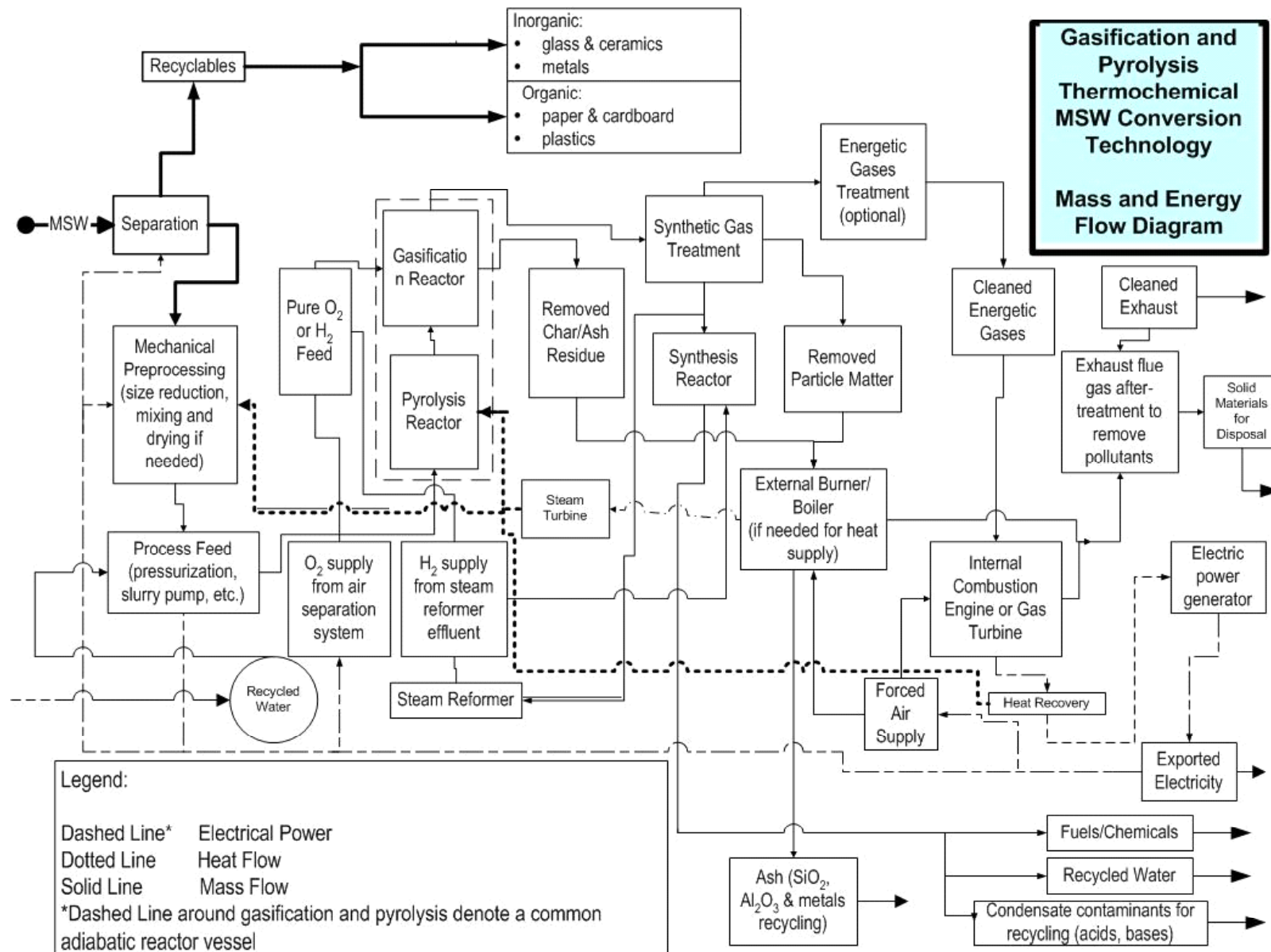


Fig. ES - 3: Schematic Diagram of Gasification Process with Front End Pyrolysis Process.

The composition of the pyrolytic/gasification products can be changed by the temperature, the pressure, the speed of the process, and the rate of heat transfer. Lower pyrolysis temperatures usually produce more liquid products and high temperatures produce more gases. Slow pyrolysis, also called carbonization, can be used to maximize the yield of solid char. This process requires a slow pyrolytic decomposition at low temperatures. A common example of this method of pyrolysis is the production of charcoal from wood.

The pyrolyzing/gasifying media can also be varied by using hydrogen and/or steam, in which case significant differences in the product distribution can occur. Such processes are currently at a research level for application to wastes, but have been investigated in greater detail for the processing of coal. Hydrogen gas can be used to enhance chemical reduction and suppress oxidation from the elemental oxygen in the feedstock. This process, known as hydropyrolysis, was originally developed to enhance the production of fuel gases from the pyrolysis of coal. Water or steam can also be incorporated into the thermochemical process to change the resultant gases and vapors and increase the porosity of the resultant char. By creating a very high surface area and porosity, activated carbon (charcoal) can be formed. Steam pyrolysis or gasification can also be used to achieve adequate results at lower temperatures but at higher pressures than processes conducted in the absence of water (so called ‘dry processes’). This ability to pyrolyze and gasify wet streams of carbonaceous material using chemically reducing processes appears to have some distinct advantages over the more traditional dry and partially oxidative methods. Most biomass materials usually contain between 25 percent and 45 percent by mass (weight) of elemental oxygen, so some oxidative reactions will occur during pyrolysis, even though additional oxygen is intentionally excluded from the process.

Plasma arc and radio frequency, or microwave heating, are techniques for providing heat from electricity for gasification, pyrolysis, or combustion depending on the amount of reactive oxygen or hydrogen fed to the reactor. Very high temperatures are created in the ionized plasma. The electric arc creates a plasma at temperatures of 7000° F and higher. The non-ionized gases in the reactor chamber can reach 1700–2200° F. The molten slag is typically around 3000° F. Plasma arc heating can provide advantages in controlling the combustion process, but at the same time there are efficiency losses due to the need to produce electricity to provide process heat. As a result of this inefficiency, plasma arc technologies were developed for specialized or hazardous feedstocks such as contaminated soils, low-level radioactive waste, and medical waste.

Catalytic cracking is a thermochemical conversion process usually applied to polymeric wastes (e.g. plastics) to produce liquid fuels (primarily gasoline). The addition of catalysts to enhance the rate of this thermochemical method has created many proprietary commercial implementations. However, the deactivation of these catalysts by the chlorine present in PVC plastics makes the general application of this technology problematic without extensive sorting and pre-treatment of the plastic from the MSW stream. The use of catalytic cracking to convert waste plastics into fuels is well established within oil refinery complexes worldwide. A catalytic cracking process is shown schematically in Figure ES-4.

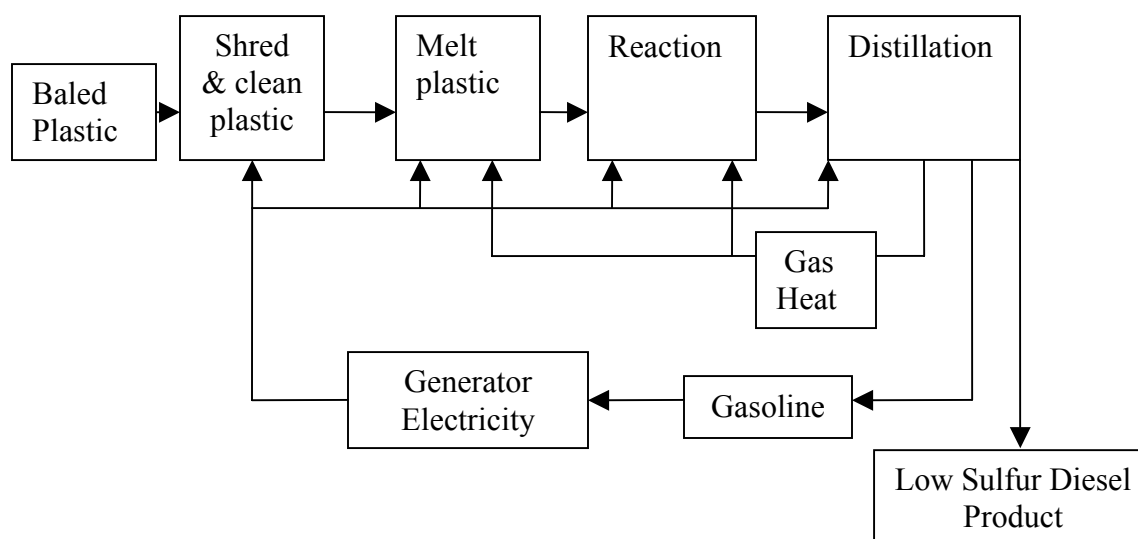


Fig. ES - 4: Schematic of a Catalytic Cracking Process using Plastic Feedstocks.

The product gases and vapors produced during the thermochemical reaction are often combusted in a separate combustion chamber that immediately follows the reactor. The thermal energy resulting from the combustion of these gaseous products can be used in a variety of ways, including steam for electricity production and heat for the pyrolysis reactor or for feedstock drying.

An important component of any combustion process is the pollution control equipment used to clean the effluent gases before exhausting to the atmosphere. The combustion of pyrolytic or gasification product gases is more efficient and produces fewer emissions than straight combustion of solid waste materials. However, emissions from gas combustion products in thermochemical processes still require emissions control to meet regulatory standards. Standard exhaust flue gas control strategies for combustion processes include particulate filters or bag houses, wet scrubber techniques, electrostatic precipitation and a number of other techniques.

Current Status of Thermochemical Processes

Gasification dates to the mid-1800s, when the technique was heavily used in the industrialization of Europe. Early gasification processes were largely developed for coal. Early advances in gasification included the Winkler fluid bed process, the Lurgi process, and the Koppers-Totzek suspension gasification process. After World War II, the use of gasification declined as petroleum became more available. In the 1970s and 1980s, several facilities began operating for production of synthetic fuels, and these remain the largest application of gasification. In the 1980s, the United States, Europe and Japan began to increase the development and deployment of gasification and pyrolysis techniques for waste. Prior to 1990, several facilities using unsorted MSW were abandoned due to technical problems related mostly to feedstock quality and handling.

A large number of gasification and pyrolysis technologies have been developed and demonstrated on levels from laboratory scale through pilot and fully commercial scale. Coal remains the predominant feedstock that is gasified, but the commercialization of gasification for waste is

growing. In general, most of the commercially identified pyrolysis and gasification facilities are operational at a level of between 100 and 500 tons per day (TPD) capacity.* In total, over 40 pyrolysis or gasification facilities commercially processing MSW were identified. The four largest technologies alone represent processing capacities of more than 2.5 million tons of MSW each year.

The use of pyrolysis and gasification for MSW has mostly been applied in Japan where landfill space and resources are limited. In examining the three largest suppliers in Japan, the capacities of their plants represent more than two million tons of material each year, with additional plants being planned. Much of this capacity has been installed in the past five years. Nippon Steel is the largest supplier with a capacity of more than 1.2 million tons of waste with more than 20 facilities. Ebara, Mitsui-Babcock, and Thermoselect/JFE operate several facilities with each company having a capacity near 400,000 TPY. Ebara is scheduled to commission a 1,500 TPD facility in Kuala Lumpur, Malaysia, in May 2006. Hitachi Metals has commissioned a 300 TPD plasma arc gasification facility in Utashinai City, Japan, with several other smaller facilities. These facilities process MSW or MSW with auto shredder residue (ASR). A number of other technologies are marketing and commercializing technologies in Japan including Hitachi-Zosen, NKK, Suminito, Kobe Steel, MHI, and IHI.

In Europe, a limited number of pyrolysis facilities are operating at a scale above 50,000 TPY for MSW or other general wastes, although a number of vendors indicated plans for development of facilities at that scale. For gasification in Europe, the SVZ facility at Schwarze Pumpe in Germany is one of the largest facilities with a capacity of 450,000 TPY of solid waste and 55,000 TPY of liquid waste. The Thermoselect Karlsruhe facility also has a capacity of over 200,000 TPY. A facility in Burgau, Germany, has been operating at 40,000 TPY since 1987. Other companies with commercially operating facilities or facilities that have operated commercially include Thide-Environmental, Serpac Environmental, Graveson Energy Management, Foster Wheeler, Emerkem, PKA, Pyromex, and Compact Power.

There are other gasification facilities operating on a smaller level or in the planning stages in Europe. These appear to be primarily niche applications or in areas where projects were supported by public agencies. The use of gasification for the processing of coal is more widely applied, and much of this technology can be utilized for processing MSW although reactor designs for MSW and biomass may be optimized differently from those designed for coal. This includes the designs by TyssenKrupp Uhde, which has over 100 gasifiers in place primarily for coal.

Several facilities in California or nearby states are operating at a small scale or are being commissioned at a larger scale including a 50 TPD thermochemical facility recently constructed by International Environmental Solutions (IES) in Romoland, California. This facility is designed for use with a wide range of feedstocks including medical waste, fireworks, MSW, bark beetle infested trees, dried sewage sludge, and tires, all of which will be tested as part of their air permitting process. Primary feedstocks planned for actual operation will include pretreated medical waste, electronic waste, bark beetle infestation trees, and fireworks. North American Power operates a similar facility in Las Vegas, Nevada. This facility is capable of processing a range of feedstocks including MSW, tires, industrial and medical waste, and liquid sludges. A catalytic cracking facility is also being planned in Hanford, California, for the processing of 50 TPD of mixed plastic waste with another 50 TPD of capacity planned for a second stage.

* Note that some facilities report capacities in tons per day and some in tons per year. For reference, 100 TPD corresponds to 36,500 TPY for continuous 24 hour/7 days a week operation or between 31,000 and 33,000 TPY for a more typical operation at 85-90% of capacity.

Pyromex AG is also actively promoting its technology in North America and California through its representative Innovative Logistics Solutions, Inc. (ILS) of Palm Desert, California. ILS currently has projects for a 400 TPD ASR facility in Anaheim, California, and a 250 TPD green waste facility in Thousand Palms, California. Pyromex also has two active facilities in Europe processing sludge. Chateau Energy Group is refurbishing a power plant in El Centro that had previously used a Lurgi fluidized bed furnace. Chateau Energy is planning to use a plasma arc gasifier consuming tire derived fuel (TDF) and natural gas generating up to 45 MW_e.

Non-combustion thermochemical conversion processes for woody biomass and some energy crops have been implemented to some degree elsewhere in North America. The FERCO gasification process, developed by Battelle, operated a gasifier co-located with a wood-fired power station in Burlington, Vermont, in preparation for installing a gas turbine. Though the gasifier operated successfully, demonstration funding was exhausted before the gas turbine was installed. Manufacturing & Technology Conversion International, Inc., has demonstrated a gasification system that has been tested with RDF, sludges, and wood waste, but could also be used for ASR and presumably MSW. For wood waste applications, Ensyn, Dynamotive and Renewable Oil International are all marketing fast pyrolysis systems. Ensyn currently has six operating units ranging in size from 40 TPD to 70 TPD in Ontario and Wisconsin with two others under construction. Ensyn is also building a commercial demonstration facility in conjunction with Ivanhoe Energy near Bakersfield, California, for processing heavy crude oil components into more valuable light components. DynaMotive will be commissioning a 110 TPD unit in Ontario, Canada, for wood waste in fall of 2004.

Gasification technologies are used commercially in the processing of coal, petroleum and natural gas to produce synthesis gas. Biomass is also gasified for heat and power, mostly in Europe and East Asia at small scales compared with coal facilities. Up to 163 gasification facilities are expected to be operating globally by 2006 representing more than 37,000 MW_{th} capacity. In the U.S., the Dakota Gasification Co. has been operating a coal gasification facility that is one of the largest in the world since 1984. The Wabash River Gasification Project in Indiana and the Tampa Electric Polk Power Station Integrated Gasification Combined Cycle project both gasify coal and pet coke on a large scale to produce power. Both have been successful projects. Eastman Chemical in Kingsport, Tennessee has operated a coal gasification facility since 1984. The syngas is used to produce commercial chemicals. The continuing expansion and maturity of gasification technology for other fuels is expected to provide a foundation that may lead to commercial scale MSW gasification in the U.S.

Several MSW conversion facilities have experienced technical or financial problems during the course of operation or commissioning. Siemens experienced considerable problems with the continuous operation of its Fürth Plant in Germany that culminated in a serious accident at the site. The accident was reportedly due to a plug of waste that formed in the pyrolysis chamber that resulted in an overpressure and escape of pyrolysis gas. European sources indicate that the problem was the result of processing full size mattresses, an issue that has been resolved in newer versions of the technology by addition of an up-front shredder. These problems caused Siemens to withdraw from the European market. A Thermoselect facility in Karlsruhe, Germany, had problems that led to considerable delays in commissioning. The 792 TPD facility was finally commissioned in 2001 and appears to have operated since then. Notwithstanding the issues with some early plants, both the Siemens technology and the Thermoselect technology have been widely applied at other facilities, so the technologies appear to be technologically sound and are among the most advanced in terms of commercialization.

A plant built by Brightstar Environmental in Wollongong, New South Wales, Australia has had problems with the char gasification component of the process and corresponding financial

problems with the plant. Technological risks remain when using alternative thermochemical conversion technologies to process heterogeneous and highly variable feedstocks such as post-recycled MSW. Given the potentially large market size and the rapid progress toward commercialization during the past five years, especially in Japan, the technology appears to be well on its way to technological maturity in terms of efficiency and reliability.

Biochemical Conversion Process Descriptions and Current Status

Biochemical Conversion Process Descriptions

Biochemical conversion technologies operate at lower temperatures and lower reaction rates than thermochemical processes. The main biochemical processes are anaerobic digestion, aerobic digestion and composting, and fermentation.

Pretreatment for biochemical processes can be performed in a number of ways. Hydrolysis is a pretreatment step whereby cellulose and hemicellulose are hydrolyzed or broken down into simple sugars that can be fermented to ethanol or other products. Fermentation is strictly an anaerobic process, but aerobic processing can be involved to make enzymes needed for hydrolysis or for making some products such as polymers from sugars. Other pretreatment methods are based on lignin removal or disruption of hemicellulose or lignin or decrystallization of cellulose.

Digestion is a term usually applied to anaerobic mixed bacterial culture systems employed in many wastewater treatment facilities for sludge degradation and stabilization. Anaerobic digestion is also becoming more widely used in on-farm animal manure management systems, and is the principal process occurring in landfills that creates landfill gas (LFG). Anaerobic digestion operates without free oxygen and results in a fuel gas called biogas containing mostly methane (CH_4) and carbon dioxide (CO_2), but frequently carrying impurities such as moisture, hydrogen sulfide (H_2S), and particulate matter.

Biogas can be used after appropriate gas cleanup as a fuel for engines, gas turbines, fuel cells, boilers, industrial heaters, other processes, or for the manufacturing of chemicals. Before landfilling, treatment or stabilization of biodegradable materials can be accomplished by a combination of anaerobic digestion followed by aerobic composting. Landfill bioreactor technology, which accelerates the rate of decomposition and improves LFG recovery and results in higher waste capacity than standard dry tomb landfills, is an emerging technology and may represent a substantial improvement over standard landfills.

Anaerobic digestion functions over a wide temperature range from the so-called psychrophilic temperature near 50° F to extreme thermophilic temperatures above 160° F. The temperature of the reaction has a very strong influence on the anaerobic activity, but there are two optimal temperature ranges in which microbial activity and biogas production rate are highest, the so-called mesophilic and thermophilic ranges. The mesophilic regime is associated with temperatures of about 95° F, the thermophilic regime of about 130° F. Operation at thermophilic temperature allows for shorter retention time and a higher biogas production rate, however, maintaining the high temperature generally requires an outside heat source because anaerobic bacteria do not generate sufficient heat. Aerobic composting can achieve relatively high temperatures (up to 160 °F) without heat addition because reaction rates for aerobic systems are much higher than those for anaerobic systems. If heat is not conducted away from the hot center of a compost pile, then thermochemical reactions can initiate which can lead to spontaneous

combustion if sufficient oxygen reaches the hot areas. Managed compost operations use aeration to provide oxygen to the bacteria but also to transport heat out of the pile.

The anaerobic digestion of lignocellulosic waste occurs in a three-step process often termed hydrolysis, acetogenesis, and methanogenesis, as shown schematically in Figure ES-5. The molecular structure of the biodegradable portion of the waste that contains proteins and carbohydrates is first broken down through hydrolysis. The lipids are converted to volatile fatty acids and amino acids. Carbohydrates and proteins are hydrolyzed to sugars and amino acids. In acetogenesis, acid forming bacteria use these by-products to generate intermediary products such as propionate and butyrate. Further microbial action results in the degradation of these intermediary products into hydrogen and acetate. Methanogenic bacteria consume the hydrogen and acetate to produce methane and carbon dioxide. A schematic of a single stage anaerobic digestion process is provided in Figure ES-6.

Fermentation is used industrially to produce products such as ethanol for beverage, fuel, and chemical uses as well as other chemicals such as acetic acid and lactic acid by anaerobic organisms or enzymes, antibiotics, and other products by aerobic organisms. Although fermentation and anaerobic digestion are commonly classified separately, both are biochemical fermentation methods that produce different products. Hydrolysis is often used to pretreat lignocellulosic feedstocks to break down the cellulose and hemicellulose from the lignocellulose and break down the compounds into simple sugars. Hydrolysis can be catalyzed by use of acids (either strong or weak), enzymes, and/or hydrothermal means, the latter including hot water and supercritical methods. A schematic of a two-stage dilute acid hydrolysis process to produce sugars followed by fermentation is shown in Figure ES-7; a concentrated acid hydrolysis followed by fermentation is shown in Figure ES-8.

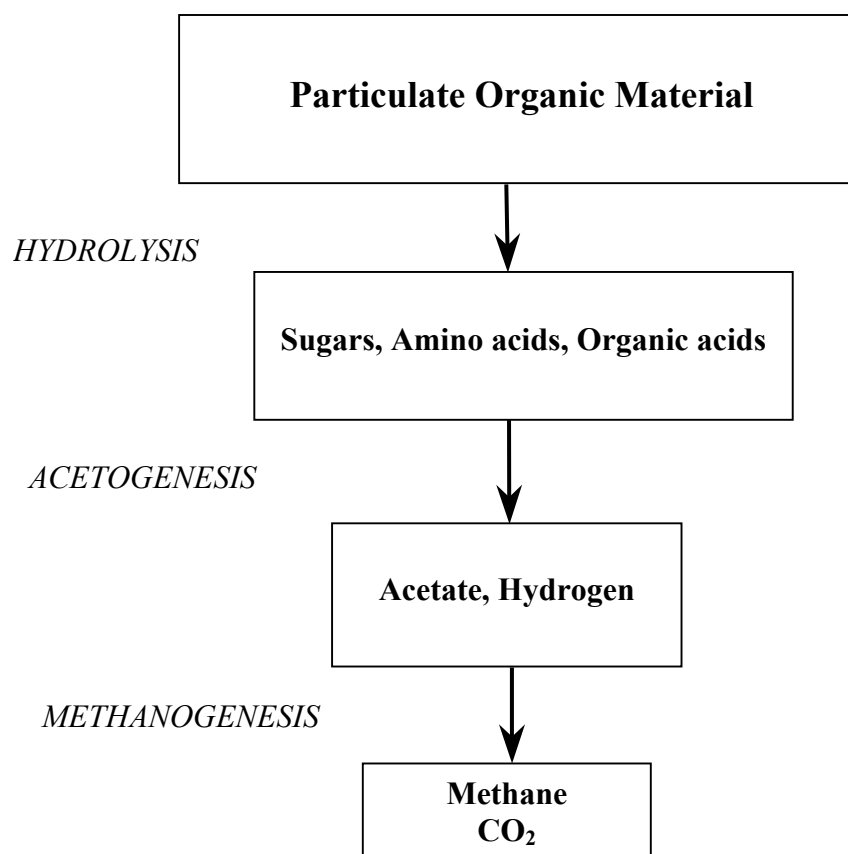


Fig.ES - 5: Anaerobic Digestion Block Diagram. Adapted from Gujer, W., and Zehnder, A. J. B. (1983). "Conversion processes in anaerobic digestion." *Wat. Sci. Tech.*, 15, 127-167.

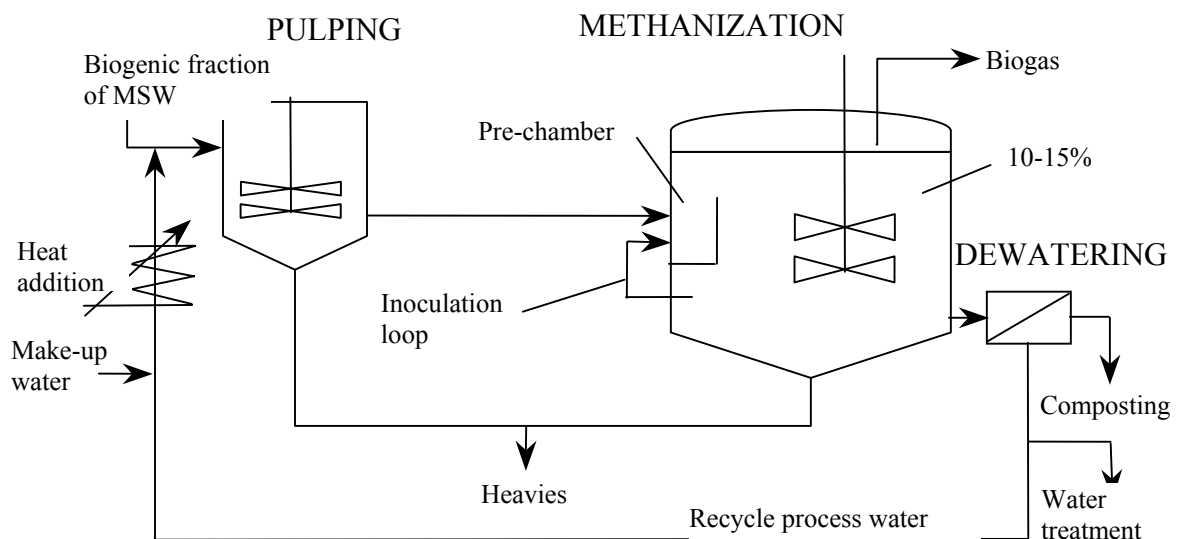


Fig. ES - 6: Schematic of Single-Stage Low Solids Anaerobic Digestion System. (Waasa, Finland)

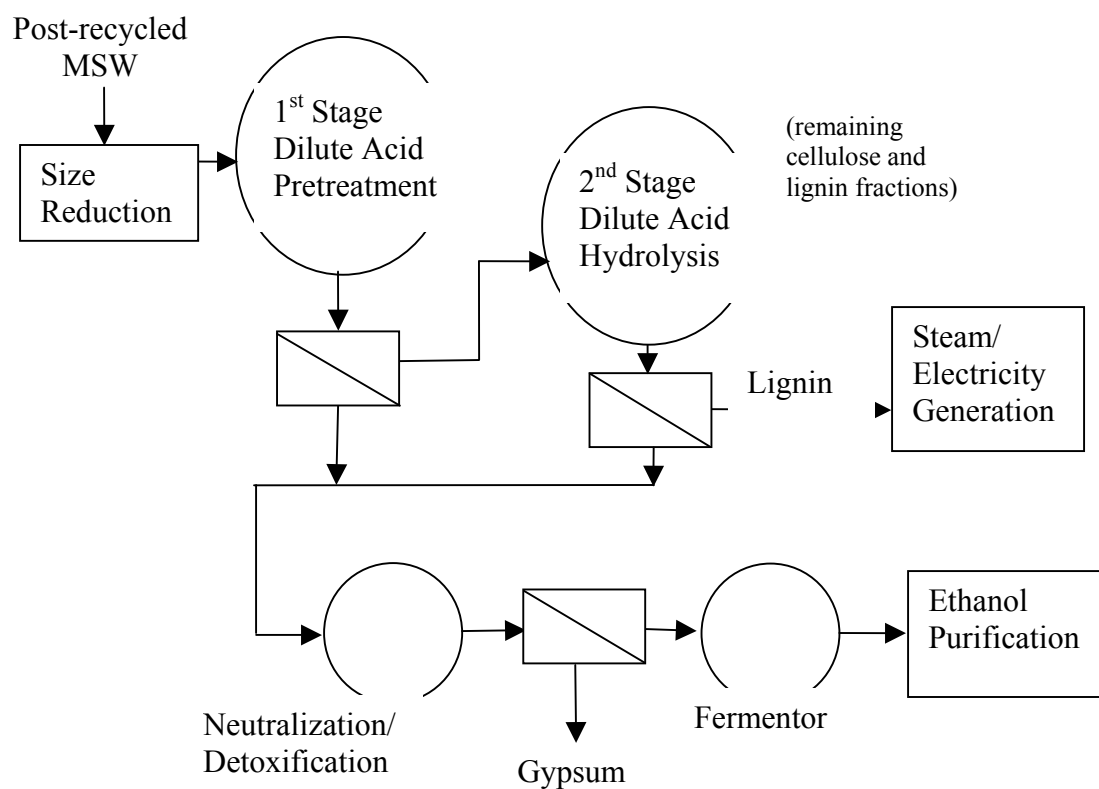


Fig. ES - 7: Schematic of Typical Two-Stage Dilute Acid Hydrolysis Fermentation.

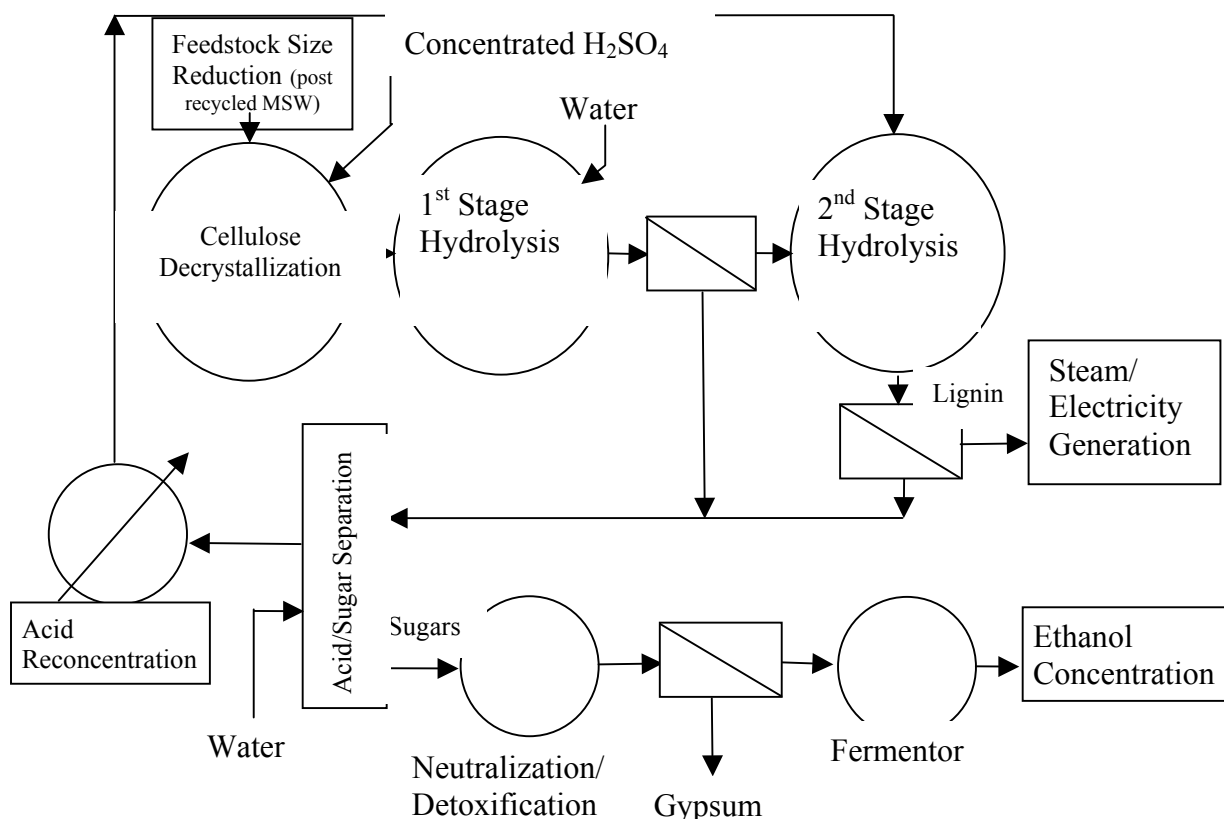


Fig. ES - 8: Schematic of Concentrated Acid Hydrolysis Fermentation. (Adapted from <http://www.ott.doe.gov/biofuels/concentrated.html>)

Ethanol can be produced once the complex molecules have been hydrolyzed and conditions made favorable (e.g., pH and temperature adjustment) for fermentation. A variety of microorganisms (bacteria, yeast, or fungi) can be employed, including recombinant organisms designed for higher productivity or specificity. Typically, 5 percent to 12 percent of the carbohydrate is converted to cell mass, which results in the most practical ethanol production processes converting no more than 46 percent of the fermented carbohydrate to ethanol. The remaining liquid broth is recycled or sent to a wastewater treatment facility for appropriate management. The lignin and other residual mass can be dried and used as compost, boiler fuel for electricity or steam production, or processed thermochemically into other fuels and chemicals. When fermenting starch materials, such as corn grain, high value feed co-products are produced. High value derivatives may also be possible from cellulosic feedstocks.

Aerobic digestion is a biochemical process for converting biogenic solid waste into a stable, humus-like product. Aerobic conversion uses air or oxygen to support the metabolism of the aerobic microorganisms degrading the substrate. Aerobic conversion includes composting and activated sludge wastewater treatment processes. Composting produces useful materials, such as mulch, soil additives and amendments, and fertilizers.

Current Status of Biochemical Processes

Anaerobic digestion systems using solid waste feedstocks are widely utilized in Europe. European Union (EU) policies have developed to minimize the amount of material being landfilled. These policies are driven by several factors including limited space for new landfills and the needs for methane emission reductions and increased renewable energy production under the Kyoto Protocol, to which the EU is a signatory. Examples of policies implemented to reduce material flow to landfill in Europe include Germany's Extended Producer Responsibility (EPR) approach, which requires manufacturers to be responsible for recovery of packaging material, and restrictions on the amount of biodegradable material that can be disposed in landfills. The result of waste management and energy policies, limited space, and high tipping fees in Europe are responsible in large part to growth of landfill alternatives including thermochemical and biochemical conversion systems.

Anaerobic digestion and/or aerobic composting of kitchen, food processor, and garden wastes is well established in Europe. To improve the quality of feedstocks used in anaerobic digestion (AD) and composting operations, source separation of household and commercial food and garden wastes is utilized extensively (at least 11 EU countries have implemented or are about to implement source separation for food and green wastes). In Switzerland, for example, approximately 220 lb per person per year of source separated food and green waste is collected. About 12 percent of the material is stabilized by AD facilities, and the balance is composted. Germany has more than 500 biochemical treatment facilities that process more than 8 million TPY of green and food wastes, with the majority being aerobic compost facilities.

There are more than 80 AD facilities in Europe with capacity greater than 3000 TPY using mandatory pre-sorted feedstock composed of at least 10 percent from municipal or commercial organic waste. Many of these facilities co-digest with animal wastes and municipal wastewater sludges. In Spain, 13 large capacity plants, averaging 70,000 TPY, are projected to be anaerobically treating nearly 7 percent of Spain's biodegradable MSW by the end of 2004. For all of Europe, the installed capacity has grown from 1.1 million TPY in 2000 and is projected to be 2.8 million TPY in 2004, an increase of more than 250 percent in four years. Figure ES-9 shows development of installed capacity of MSW AD facilities in Europe between 1990 and 2004. The annual capacity growth rate is above 20 percent. Single-stage anaerobic digesters account for approximately 92 percent of this installed AD capacity.

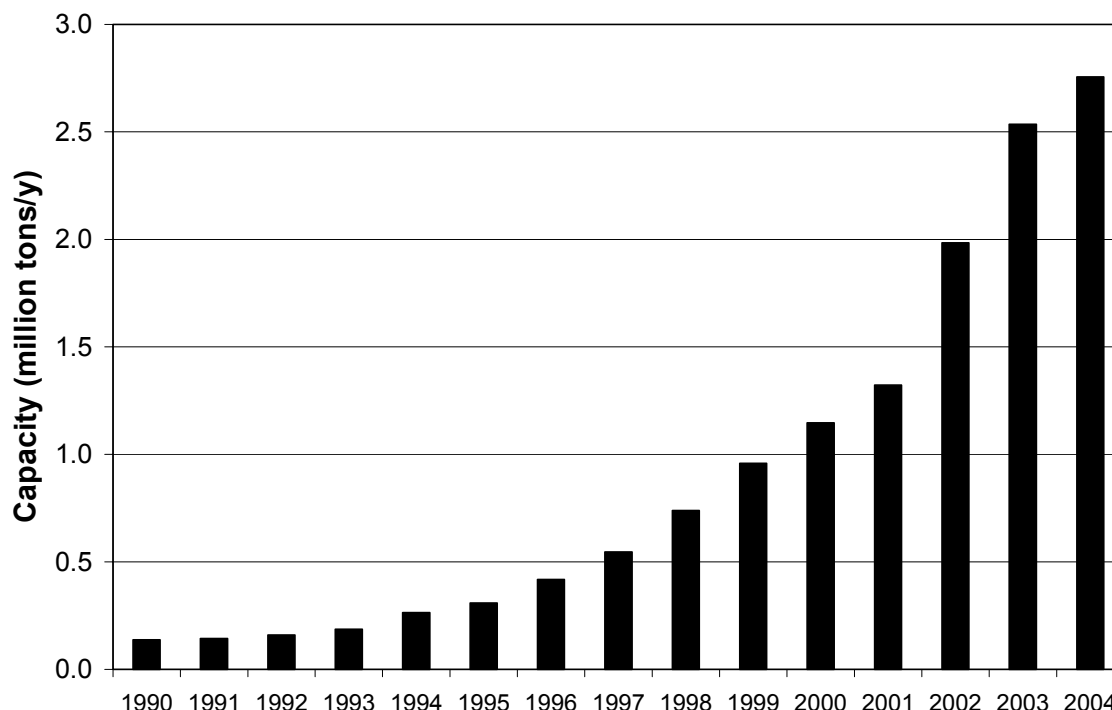


Fig. ES - 9: Growth Solid Waste Anaerobic Digester Capacity in Europe.

Adapted from L. DeBaere (2003)

*Data were projected for 2004

Fermentation of biomass into ethanol is fully commercial for sugar and starch based feedstocks. It is not yet commercial for cellulosic biomass because of technical difficulties and cost, but this remains an active area of research and development. However, there are several facilities that are being commissioned. The Masada OxyNol process is permitted and expected to begin construction soon in Middletown, NY. This facility is permitted for 230,000 TPY of MSW and 71,000 bone dry TPY of biosolids with an expected annual output of 8.5 million gallons of ethanol. A facility is also planned by Genahol Inc. in Grove City, OH. The facility will be designed for a 275,000 TPY capacity and will process cellulosic and other biomass components of MSW. The annual yield is expected to be ten million gallons of ethanol. Other examples of cellulosic biomass to ethanol commercialization attempts include Iogen in Canada, BCI in Louisiana, and Arkenol with a plant in Japan. Initially, feedstocks in these ventures are intended to be agricultural and wood based residues. Both BCI and Arkenol proposed commercial projects in California but have not yet completed successful technology demonstrations in the state.

With respect to California, other than one operating full-scale landfill bioreactor demonstration project, there are no existing MSW biochemical processing facilities using anaerobic digestion or fermentation methods in the State. This is due to relatively low landfill tipping fees, low wholesale prices of product energy (methane or electricity), general lack of source-separation at the waste generation site, and lack of restrictions on landfilling of biodegradable material. There are several in-vessel digester projects proposed including a commercial scale facility for California State University – Channel Islands and a demonstration pilot scale facility at the University of California, Davis, both using a design developed at UC Davis. Recent announcements indicate that Los Angeles and the City of Lancaster are investigating anaerobic digestion projects with Bioconverter LLC. In at least two California jurisdictions that are investigating alternatives to landfilling, biochemical conversion is ranked either among the

finalists or as the only qualifying process. A number of digestion projects are in development under state incentive programs for animal and food processing wastes.

Products of Thermochemical and Biochemical Conversion Processes

Thermochemical gasification processes are optimized to produce either fuel gases to be used in a mechanical or electrical power conversion process or synthesis gas to feed secondary chemical or fuel production processes.

The products of gasification and pyrolysis can be utilized in a range of secondary applications. A common application in many current installations is the combustion of the conditioned product gases to provide electricity or process heat. Advanced technologies employing combined cycles or fuel cells can generate electricity at higher efficiencies than simple steam-cycle mass burn systems. Gas storage prior to electrical conversion and the production of liquids both offer the capability to generate electricity on-peak as opposed to the base load operation of large mass-burn facilities. The value of the electricity is therefore substantially higher than for base loaded plants.

Storable gas, liquid, and solid fuels and chemicals can be produced by alternative techniques discussed here. The secondary processing of synthesis gas can be used to produce a range of liquid fuels and chemicals including methanol, dimethyl ether (DME), Fischer-Tropsch diesel fuel, hydrogen, synthetic ethanol, or substitute natural gas. For the production of these fuels or synthetic chemicals, the synthesis gases from gasification processes generally require less additional processing to produce valuable products than any other form of conversion technology other than the methane-rich biogas produced through anaerobic digestion. From an environmental perspective, the production of fuels and chemicals can provide environmental benefits in emissions reductions.

Products of biochemical processes include biogas, ethanol, and other alcohols for use as fuels or as chemical feedstocks. Biochemical processes can also be used to produce higher value chemical products. Biogas can also be upgraded to natural gas pipeline quality and compressed for use as a transportation fuel much like compressed natural gas (CNG). Ethanol is produced from a fermentation process and then distilled and dehydrated to yield fuel-grade ethanol. Ethanol can serve as an intermediate for hydrogen production, and may not require distillation with some autothermal catalytic reforming processes in research and development.

Digestate from digestion processes including lignin and other non-degraded components of the waste can be processed for fertilizer and soil conditioning applications. Alternatively, the material can be used in compost or dried and used as a boiler fuel for heat and power or converted to fuels through thermochemical means.

Environmental Impacts

Environmental implications of alternative conversion technologies are critically important to the overall feasibility of these processes. While a number of studies have characterized emissions from individual alternative waste conversion processes, there is a lack of consistent comprehensive data for use in comparative analyses to make broad conclusions within and among technology classes. This is due to the wide variety of process configurations and control strategies that are uniquely applied to individual facilities and to the general immaturity of the technologies as applied to MSW. Most commercial facilities worldwide are evaluated on a case-by-case basis by regulatory agencies. There are, however, a number of facilities that provide emissions data from processes that employ similar pollution control strategies to those that would be used for

alternative technologies in the state. Some of these data are useful in predicting potential environmental impacts of proposed facilities in California. In addition, there are alternative waste conversion sites under development in California. Direct measurements from these facilities are planned as these sites begin operation, providing for objective independent testing and verification of environmental performance.

Current information suggests that thermochemical and biochemical waste conversion processes can be operated in a manner that presents no greater threat to human health or the environment than current waste disposal practices such as mass burn incineration or landfilling. That being said, properly designed processes must adequately address air emissions, water quality, solid and liquid wastes, nuisance factors, and health and safety risk factors.

Air Emissions

While biochemical processes have gained widespread acceptance for treating various feedstocks, thermochemical processes have met with resistance from the environmental community and the public. Some of this resistance has stemmed from the misperception that pyrolysis and gasification processes are only minor variations of incineration or “mass burn.” An essential difference between combustion (incineration), pyrolysis, and gasification is that the latter two are intermediate processes for producing gaseous, liquid, and solid products that can be used in a wide variety of applications. For the broader category of coal and petroleum gasification, the production of chemicals, fuels, and synthetic gases is actually more prevalent than electricity production. Pyrolysis processes can be optimized for the production of oils. In the case of chemical and fuel production, the emissions from a direct process effluent can be avoided, although consideration must be given to emissions from the ultimate use of these products as they are used or combusted downstream. Nevertheless, these downstream-use emissions would tend to be more dispersed rather than concentrated at a single site location, and might displace emissions from other sources, such as natural gas combustion, petroleum refining, and motor vehicle use of gasoline or diesel.

Although chemical and fuel production from gasification and pyrolysis of MSW components is possible, the most prevalent process is the use of producer gases for on-site electricity production. These post-combustion processes associated with alternative thermochemical conversion processes still differ dramatically from incineration in several key respects:

- Pyrolysis and gasification processes use lower amounts of air/oxygen or none at all.
- The volume of output gases from a pyrolysis reactor or gasifier is much smaller per ton of feedstock processed than that from an incineration process. While these output gases may be eventually combusted, the alternative processes provide an intermediate step where gas cleanup can occur. Mass burn incineration is limited in application of air pollution control equipment to the fully combusted exhaust only.
- Output gases from pyrolysis reactors or gasifiers are typically in a reducing environment, and can be treated with different technologies compared with a fully combusted (oxidative) exhaust. Reactant media can also be hydrogen or steam.
- Subsequent combustion of low molecular weight fuel gases from pyrolysis and gasification processes can be much cleaner than combustion of raw feedstocks .

These factors make control of air emissions less costly and less complex than that required for incineration.

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While exhaust gas cleanup of non-combustion thermochemical conversion processes may be easier than that associated with incineration, proper design of the process and emissions control systems is necessary to ensure that health and safety requirements are met. The output products of pyrolysis and gasification reactors can contain a variety of potential process and air pollutants that must be controlled prior to discharge into the ambient air. These include particulate matter (PM), aerosols or tars, oxides of nitrogen (NO_x), oxides of sulfur (SO_x), dioxins and furans, hydrocarbon (HC) gases, multiple metals, and carbon monoxide (CO). There are many strategies for controlling emissions from thermochemical conversion processes, and they are highly dependent on the process requirements of each individual facility.

Contaminant removal from the exhaust stream is typically accomplished with a variety of technologies described in Table ES-2. These are often used in combination. As noted above, thermochemical conversion processes may employ air pollution control at the reactor outlet as well as the exhaust gas outlet.

Table ES-2 – Air Pollution Control Technologies

Contaminant	Control Technology
Particulate Matter (PM) and Aerosols	Inertial Separation, Baghouse, Scrubbers, Electrostatic Precipitators (ESP)
Volatile Metals (vapor state)	Carbon Filters (or condense to PM or aerosols and use PM separation techniques)
Dioxin/Furans	Limit chlorine mass input in feedstock, Cold-quenching and/or Catalytic/thermal Combustion
Carbon Monoxide (CO) and Hydrocarbon (HC) gases	Process Design, Catalytic/thermal Combustion, Re-burning, Carbon Filters
Oxides of Nitrogen (NO _x)	Flame Temperature Control/ Low NO _x Combustors, Fuel Nitrogen Management, Selective Catalytic Reduction, Water Injection, Re-burning
Oxides of Sulfur (SO _x)	Limit sulfur mass input. Scrubber
Acid Gases	Scrubber

Emissions of dioxins and furans are an important environmental consideration. Dioxins and furans are compounds consisting of benzene rings, oxygen, and chlorine that are considered or known to be toxic or hazardous. Dioxins and furans can form when waste streams containing chlorine are processed under conditions where the flue gas has a significant residence time in a

temperature range between 480 and 1290° F, with a maximum formation rate at approximately 600° F. They are typically formed downstream of the combustion process and frequently within the air emission control equipment. In this temperature range, hydrogen chloride (HCl) in the flue gas reacts with oxygen to form chlorine (usually catalyzed by heavy metal vapor, such as copper) and the chlorine subsequently reacts with hydrocarbon radicals to form dioxins and furans. The low levels of oxygen present in pyrolysis and gasification processes inhibits the formation of dioxins and furans (however HCl in product gas must be managed if combustion for heat or power follows gasification). Chlorine is an essential element in the formation of dioxins and furans, but studies of the impact of chlorine concentration in the feedstock on their formation give mixed results. For studies that have shown correlations between chlorine and dioxin and furan formation, a strong correlation is typically only observed at levels above 1-2 percent in the feedstock.

Some studies have shown the formation of dioxins and furans during pyrolysis of feedstocks containing chlorine, with most the dioxins and furans found in the product oils. Other studies have shown that removal of HCl in the flue gas using scrubbing techniques can reduce dioxins and furans to acceptably low levels, even for feedstocks containing up to 8 wt. percent chlorine. Alternatively or in addition to scrubbing, high-temperature combustion of intermediate gases can prevent de novo formation and destroy dioxins and furans already present. High-temperature combustion is, in fact, the recommended treatment for landfill gas collection systems. Aside from air pollution control measures, the amounts of chlorine and copper in the feedstock can also be limited to minimize potential formation.

Solid Waste Residues

Heavy metals present in feedstocks are concentrated in ash or residual solids produced by virtually all conversion technologies. With proper management, the concentrated heavy metals can more readily be treated and disposed of in a controlled manner that poses lower environmental threat. In some cases, metals may even be recycled from the char/ash. In some processes, the ash is vitrified to form a slag. The slag is a hard, glassy substance that is formed when the gasification systems operate above the fusion or melting temperature of the ash. Since the non-volatile metals are fused into the slag, leaching of metals is reduced or eliminated. When demonstrated to be safe and metals sufficiently stabilized, the bottom ash and slag could be used in different construction and other applications.

Solid residues, mostly as cakes or powders of fine particulate matter, are generated by baghouse filters and electrostatic precipitators (ESPs) that are periodically cleaned. Bottom ash is also produced in some cases. For example, fluidized bed reactors may rely on sand and other inorganic material present in the fuel as make-up for the bed media lost through attrition (and mostly captured in the PM control system). Some of this material is periodically discharged to maintain proper bed level in the reactor. The discharged material may be useful as road aggregate, agricultural soil additive, or may be landfilled.

Significant quantities of solids remain following biochemical processing of MSW. This includes virtually all the lignin and some non-degraded cellulose or other carbohydrates. Much of this can be processed for fertilizer and soil conditioning applications, especially following aerobic composting, or used as a boiler fuel for heat and power or converted to fuels via thermochemical means.

Liquid Wastes

Liquid wastes generated by alternative waste conversion processes include pyrolysis oils, spent acid solutions from acid hydrolysis in biochemical systems, boiler blowdown in thermochemical processes employing boilers, and spent scrubber solutions from air pollution control equipment. There are well-defined mechanisms already in place for dealing with spent acids and scrubber solutions although treatment costs can be high. Gas cleaning systems for gasification and pyrolysis in some designs also produce waste water or waste liquid streams that may contain tars, oils, chars, ash, and other constituents removed from the raw process stream. Pyrolysis oils are composed of a range of hydrocarbon compounds. Although some of these compounds can be toxic, they are also compounds commonly used in other industrial processes and may be recoverable in some form as commercial products.

Nuisance Factors

The nuisance factors associated with alternative waste conversion technologies can include noise, odors, fugitive emissions, dust, litter and debris, increased local traffic, aesthetics, and vectors. In general these impacts would not be expected to increase and may be reduced compared with what is experienced in existing solid waste facilities. The use of engines, turbines, and generators to produce electricity may result in increased noise, but this is commonly mitigated by enclosing the generating equipment in sound isolating enclosures. Conversion processes generally occur in an enclosed vessel so that odors, fugitive dust, and litter are not typically associated with the reactor component of the system. Co-location of conversion facilities at existing solid waste facilities will not result in any increased traffic because the existing transportation infrastructure can be used and material can be transported via conveyor belts. Traffic impacts may exist due to offsite transportation of commercial products and byproducts for marketing and disposal.

Other Risks

Other risks associated with conversion technologies may include potential acid or other chemical spills and leaks or breaches in high-pressure lines and reactors. These risks should be adequately managed by proper design and accommodated within other well-defined risk abatement mechanisms already in place for industrial processes. As with any new technology implementation, there may remain unforeseen risks until adequate experience is obtained.

Environmental Conclusions

From an environmental perspective, advanced alternative waste conversion technologies have several potential benefits over mass incineration or other current practices. Existing data and facilities indicate that alternative conversion technologies can operate within existing regulatory constraints. Facilities with the most advanced environmental controls would very likely be able to meet regulatory requirements in California. The actual impacts of specific facilities will need to be evaluated on a case-by-case basis as part of a local permitting process.

Socio-Economic Impacts of Alternative Conversion Processes

As a resource, the organic portion of the MSW materials being buried in California landfills each year represents an estimated chemical energy equivalent to more than 60 million barrels of crude

oil, sufficient to generate 2370 MW of base load electrical power. At a market price of over \$37 per barrel, this energy resource could be considered to be worth more than \$2 billion. For thermochemical processing, plastics are a particularly attractive component of the landfilled MSW stream, since they represent over 30 percent of the chemical energy in California MSW and are growing at almost twice the rate of biogenic organic materials.

The broad implementation of conversion technologies could affect the state economy in a number of different ways, including the introduction of new sources of products and energy, the diversification of product markets, extension of landfill lifetimes, increased recycling, decreased environmental impacts, job creation, and the specific economic impacts related to the plant itself.

Because California landfills a large amount of material that could be used as energy and material process feedstocks, significant positive economic impacts are possible. The application of conversion technologies to the waste stream could provide up to 8 percent of the state's current electricity consumption and help in achieving the goal of 20 percent renewable energy by 2017 required under the California Renewables Portfolio Standard Program (RPS).[†] Other significant product streams could include a wide range of liquid fuels and chemicals. The introduction of new production facilities could also provide a beneficial diversity of markets. This could reduce the state's dependence on imported petroleum resources or out-of-state electrical resources and ethanol.

Another potential societal benefit could be the extension of landfill space by directly diverting materials from the landfill. This could reduce the burden and need to permit new landfills and could facilitate improvements in land use practices.

In general, the use of conversion technologies around the world is fairly limited, although they are beginning to be implemented more widely in Japan and Europe. Energy markets and waste management policies in Europe and Japan combine to create conditions for commercializing combustion and non-combustion solid waste conversion systems. The economics for individual facilities in California will be site specific as the primary economic competition is the standard landfill. Most, if not all, systems reviewed rely on tipping fees to be economically viable. As such, a decrease in tipping fee rates, which could result from direct competition with landfills for material, would likely cause financial stress or failure of the project. Future measures that increase diversion of generated waste or place restrictions on the content of landfilled waste (an example would be to limit or ban biodegradable waste components or restrict average total organic carbon content) will help provide incentives for further diversion and waste reduction as well as implementation of conversion technologies. Several jurisdictions in California are conducting evaluations of landfill alternatives including the cities of Alameda, Los Angeles, and Hanford, and Santa Barbara County, Los Angeles County, and the Coachella Valley Association of Governments.

The impact from extensive adoption of conversion technologies is of great concern to the existing recycling and composting markets, landfill industry, waste reduction advocates, and landfill gas-to-energy producers. With the development of alternative conversion technologies that can process a broad range of waste, some of the difficult to recycle materials may find a market in conversion. On the other hand, wider use of conversion technologies would likely result in greater effort in processing or sorting waste streams that are currently being sent directly to landfills.

[†] Electrical potential from the renewable (biogenic) portion of the stream is equivalent to about 50% of the current amount of renewable electricity used in the State from all sources. To the extent that plastics made from petroleum or tires are used in conversion to energy, that portion of the energy produced would not be considered renewable.

These offsetting factors were evaluated as part of a market study being conducted in conjunction with the life cycle analysis (LCA) project. The marketing study estimates that recycling rates for paper would be unchanged by conversion technology implementation, metal and glass recycling rates would increase for both biochemical and thermochemical processes, and the plastic recycling rates would increase only for biochemical processes. On balance, conversion technologies are expected to augment recycling and composting activities, but some individual facilities may compete with traditional recycling and composting for feedstocks. However, it should be recognized that conversion technologies designed to produce fuels or other chemical based products such as ethylene from waste plastics or other materials represent another pathway for material recycling and can displace petroleum and other fossil feedstocks. The efficacy or efficiency of this type of material recycling should be compared to conventional recycling using an equal outcome basis.

Conclusions

On the basis of the information evaluated in this report, thermochemical and biochemical conversion technologies represent technically viable options for the conversion of post recycled MSW. Thermochemical and biochemical technologies are processes with unique characteristics that have different applications in reducing landfill volume. In some cases, combinations of these technologies are likely to be used in addressing post-recycled MSW (i.e., ecoparks).

Thermochemical conversion technologies, such as gasification and pyrolysis, can treat nearly all of the organic fraction of MSW and can, in general, treat a more heterogeneous feedstock, including high energy content plastics. Pyrolysis and gasification applications for MSW have expanded considerably in the past five years, especially in Japan that has limited domestic resources and limited landfill space. Over 50 commercially active facilities were identified with a total capacity representing approximately 8 percent of the current landfill stream in California. Of the two methods, gasification is more technologically complex but offers the capability of producing a broader array of products without additional upgrading.

The use of alternative biochemical technologies for processing fractions of the MSW stream has also increased significantly during the past five years. This includes processes such as anaerobic digestion and fermentation. Biochemical technologies are more limited in their application since they can only process biodegradable feedstocks. Most of the growth in biochemical technologies has been in Europe and is due to a combination of high tipping fees, restrictions on landfilling untreated waste, and high prices for renewable energy products. Currently, the European capacity of anaerobic digestion for MSW components represents approximately 7 percent of the current landfill stream in California. Biochemical technologies could also be used in combination with alternative thermochemical or other processes to provide broader reduction of landfilled material.

Feedstock selection and processing will depend on the specific requirements of each conversion technology being used as well as other local economic considerations. It is anticipated that conversion processes will use more up-front sorting processes to remove inorganic metals, and other potentially recyclable materials such as paper and some plastics. Additional sorting would likely be required for biochemical process to provide an input stream that is composed of essentially biodegradable products. This would exclude the majority of the plastic and textiles, although these materials can be accepted, but are not transformed, in some biochemical processes. For thermochemical processes, materials that would contribute to toxic or other air pollutants could also be removed, if necessary. This could include feedstocks with high Cl content such as PVC or other feedstocks with significant quantities of volatile metals such as batteries. Air pollution controls will be needed in addition to the preliminary sorting so that a complete clean sort would not likely be required.

Conversion technologies provide the potential of converting materials that are currently landfilled into electricity, chemical, or other products such as synthetic diesel and gasoline transportation fuels, or precursors of petrochemical feedstocks such as ethylene, hydrogen, substitute natural gas and others.

Existing data and facilities in locations around the world indicate that conversion technologies can operate within constraints established by regulatory requirements. There has also been considerable technological progress in emissions controls over the past decade that can be directly applied to alternative conversion technologies. These factors indicate that it is very likely that conversion technologies with the most advanced environmental controls would be able to meet regulatory requirements in California. The environmental risk of alternative conversion technology facilities appears to be comparable with other common industrial practices provided the facilities are properly designed. However, the actual impacts of specific facilities will need to be evaluated on a “case-by case” basis as part of the local permitting process.

The viability of any single facility will depend on a number of factors including economic considerations, facility capital costs, and feedstock requirements and availability. While facilities are becoming operational throughout the world, the technological and economic risk will be facility-dependent. Given the heterogeneous nature of MSW feedstocks and the volatility of tipping fees and product prices, some risk remains with the use of conversion technologies. A number of facilities were identified that were unsuccessful for a variety of technical or economic reasons. Considering the potentially large market size and the rapid progress towards commercialization, however, conversion technologies appear to be well on their way to technological maturity with good efficiency, reliability, and environmental performance.

Recommendations

The following are recommendations related to the area of alternative conversion technologies.

- It is suggested that the definition provided in AB 2770 for gasification be revised to provide a more scientifically correct description of the gasification process, if needed. An improved definition is contained in this report as follows:

“Gasification refers to conversion of solid or liquid carbon-based materials by direct internal heating provided by partial oxidation using substoichiometric air or oxygen to produce fuel gases (synthesis gas, producer gas), principally CO, H₂, methane, and lighter hydrocarbons in association with CO₂ and N₂ depending on the process used.”
- A more formal evaluation should be conducted of conversion technology vendors interested in marketing in California. This evaluation should include more specific information than can be obtained in a scoping study such as the present work. This information should include economic cost estimates, emissions data from third-party sources, and more specific detail on commercial status, including possible site visits for a limited number of already commercialized technologies. This evaluation should be conducted by a neutral, independent, third party.
- The State should investigate conversion technologies including, perhaps, sponsorship of a reasonable pilot scale demonstration facility within California which can be rigorously analyzed and operated with full public participation in order to develop

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verifiable and trusted operational data. A steering committee of stakeholders should be included at the outset.

- Improve the characterization of MSW. To predict the behavior of conversion systems and estimate type and quantity of emissions, detailed chemical composition and physical property data for feedstocks are necessary. Much information exists in the literature, but a review should be done to determine whether sufficient data exist for California waste streams. Where gaps are identified in the data, samples of California waste streams should be analyzed to fill these information gaps. The type of characterization by component and by gross sample includes:
 - Proximate, ultimate, and other elemental analysis including ash, metals, and toxic cogeners
 - Higher heating values (HHV)
 - Structural carbohydrate analyses (cellulose/hemicellulose/lignin) for cellulosic components
 - Protein/carbohydrate/fats for typical food and other wastes

Recommendations could be made on the basis of these results as to which components should be pre-sorted from MSW being used for conversion.

- Additional data should be collected on emissions from thermochemical and biochemical conversion technologies. These emissions studies should be conducted by an independent third party and could include facilities at locations throughout the world, or most importantly in California as facilities become available. These emissions studies should include measurement of metals, dioxins and furans, other hazardous compounds, and fugitive gas and particulate matter emissions, in addition to criteria pollutants. The emissions results should be normalized to a standard use indicator such as volume or mass of material processed so that the values can be compared with other processes. These characterizations are typical of the type performed in life cycle assessment. Measurement of the composition of synthesis gas and other products prior to any combustion may also be useful in evaluating the system as a whole.
- Create co-funding methods to encourage the commercial development suitable for MSW conversion facilities. These could be co-located with existing landfills, material recovery facilities (MRFs), and other waste handling operations for maximum effectiveness in promoting reduction of mass flows into present landfills.
- Investigate issues and feasibilities of “complete stream recycling parks” (aka “ecoparks”) where current waste material enters the facility, is sorted and sent to processes that make best use of the material. Ideally, there would be no unvalued residues left for disposal.